Acceleration and Focusing Measurements in Beam-Driven Plasma Wakefields at ATF

Phys. Rev. Lett. **91**, 014802 (2003)

Cohesive Acceleration and Focusing of Relativistic Electrons in Overdense Plasma

V. Yakimenko,[1] I. V. Pogorelsky,[1] I. V. Pavlishin,[1] I. Ben-Zvi,[1] K. Kusche,[1] Yu. Eidelman,[1] T. Hirose,[2] T. Kumita,[3] Y. Kamiya,[3] J. Urakawa,[4] B. Greenberg,[5] and A. Zigler[5]

[1]*Accelerator Test Facility, Brookhaven National Laboratory, 820, Upton, New York 11973, USA*
[2]*Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo 169-8555, Japan*
[3]*Department of Physics, Tokyo Metropolitan University, Hachioji-shi, Tokyo 192-0397, Japan*
[4]*KEK (High Energy Accelerator Research Organization, Tsukuba-shi, Ibaraki 305-0801, Japan*
[5]*Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel*

(Received 2 January 2003; published 3 July 2003)

We describe our studies of the generation of plasma wake fields by a relativistic electron bunch and of phasing between the longitudinal and transverse fields in the wake. The leading edge of the electron bunch excites a high-amplitude plasma wake inside the overdense plasma column, and the acceleration and focusing wake fields are probed by the bunch tail. By monitoring the dependence of the acceleration upon the plasma's density, we approached the beam-matching condition and achieved an energy gain of 0.6 MeV over the 17 mm plasma length, corresponding to an average acceleration gradient of 35 MeV/m. Wake-induced modulation in energy and angular divergence of the electron bunch are mapped within a wide range of plasma density. We confirm a theoretical prediction about the phase offset between the accelerating and focusing components of plasma wake.

DOI: 10.1103/PhysRevLett.91.014802 PACS numbers: 41.75.Lx, 41.75.Ht, 52.35.–g

Plasma-based accelerator schemes use laser (LWFAs) or electron beams (PWFAs) to drive plasma waves that induce ultrahigh acceleration gradients not achievable with conventional radio-frequency accelerators. The PWFA mechanism [1] uses a highly relativistic electron beam propagating in plasma to excite a large amplitude wake field that can accelerate a second trailing electron bunch to high energy. Recognizing that precise control of the transverse dynamics of an accelerating beam is crucial for reaching the necessary high luminosity in an accelerator, features of the motion of transverse particles have attracted considerable interest.

A fundamental feature of wake field acceleration is the phase offset between the longitudinal and radial forces in the wake. This statement follows from the Panofski-Wenzel theorem [2] that relates these forces by the equation

$$\frac{\partial E_z}{\partial r} = \frac{\partial (E_r - B_\theta)}{\partial \xi}, \qquad (1)$$

where $\xi = (k_p z - \omega_p t)$. For a linear regime, these forces take a simple analytical form

$$E_z \propto \cos\xi, \qquad E_r - B_\theta \propto r \sin\xi, \qquad (2)$$

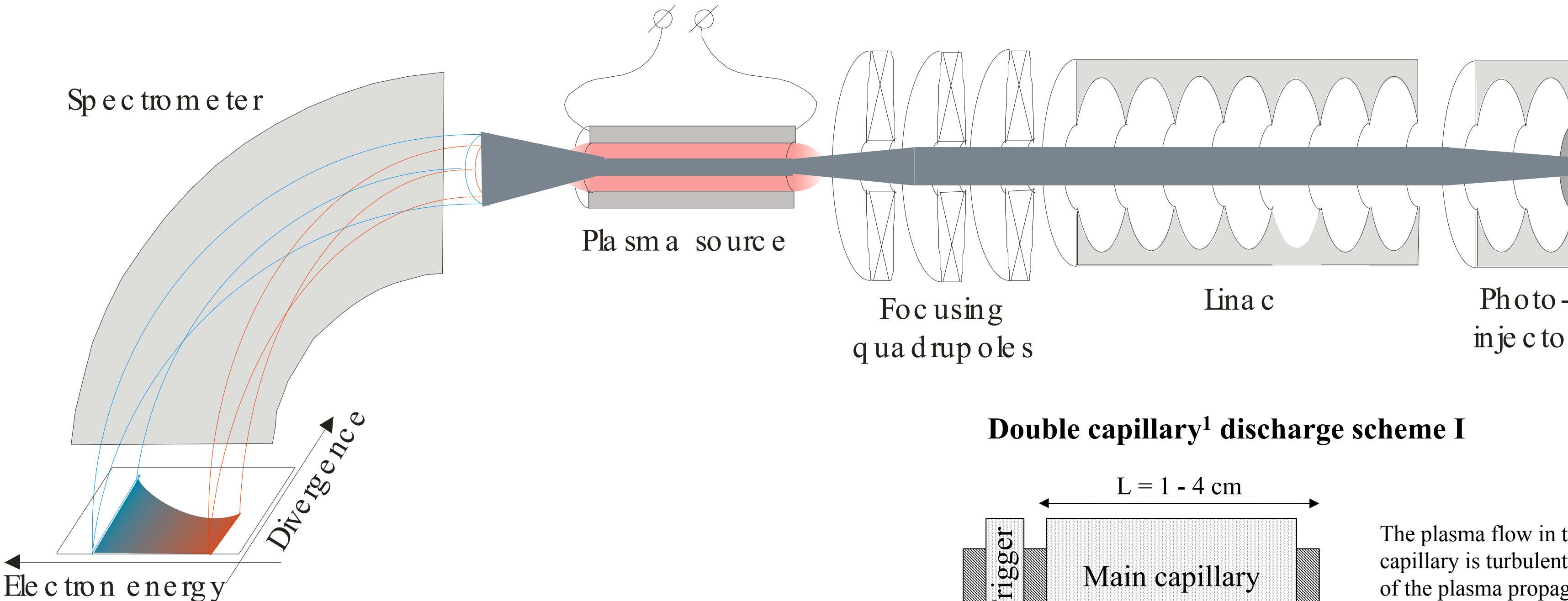
implying that there is a $p/2$ phase offset between the longitudinal and radial fields. Thus, attaining stable acceleration in the plasma's wake field requires precisely placing the accelerated particles in the relatively narrow window within the wake, where both acceleration and focusing are maintained simultaneously.

In Experiment E157 at SLAC, a change in plasma focusing was observed along the bunch, using an externally imposed energy chirp [3,4]. Yet, although this finding was fundamentally important, the phasing between the accelerating and focusing components in the wake field lacked empirical verification. Our study provides the first observation of such phase correlation in the linear overdense regime, $n_e \gg n_b$. This regime fosters a simplified analytical treatment, yet still offers the maximum accelerating fields for technically achievable bunch charges, provided that the resonance condition between the plasma and electron bunch is attained. We will show that our experiment met this condition.

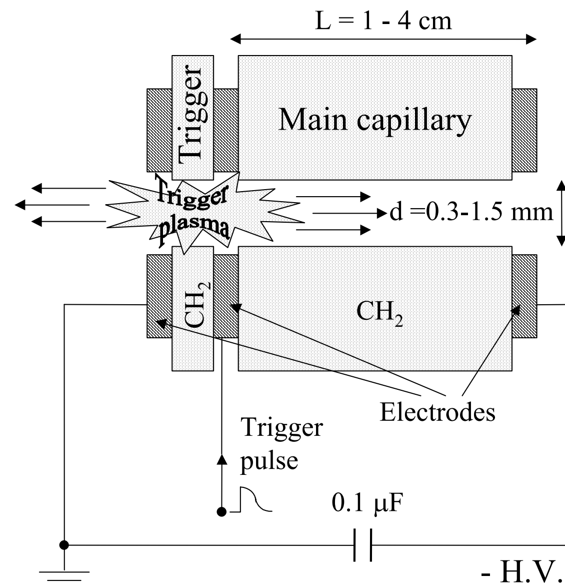
The PWFA experiment, set in beam line 1 of the Brookhaven Accelerator Test Facility, used as a plasma source a 60-MeV electron beam produced by a photocathode rf electron gun followed by rf linac and a capillary electrical discharge. The plasma source is described in detail elsewhere [5]. The polypropylene capillary was 17 mm long with an inner diameter of 1 mm. It was mounted on a combination of translation and tilt manipulators to align the capillary along the path of the electron beam. The electron density of the highly ionized carbon-hydrogen plasma, produced by applying a 20-kV voltage pulse to the capillary's electrodes, reached $n_e \sim 5 \times 10^{17}$ cm^{-3}. Off-line optical interferometry [6], MHD simulations, and measurements of the CO_2 laser-energy absorption confirmed this number. Lower density levels can be obtained easily in the afterglow plasma after terminating the discharge.

The $E_e = 60$ MeV, 300 pC, 1.5 ps (rms) long electron beam was focused to an rms spot size of $\sigma_r \sim 100$ μm in the capillary discharge by upstream quadrupole triplet magnets. Because of ballistic compression in the linac, the electron beam is not Gaussian in time. It has a

Experimental setup



Double capillary[1] discharge scheme I



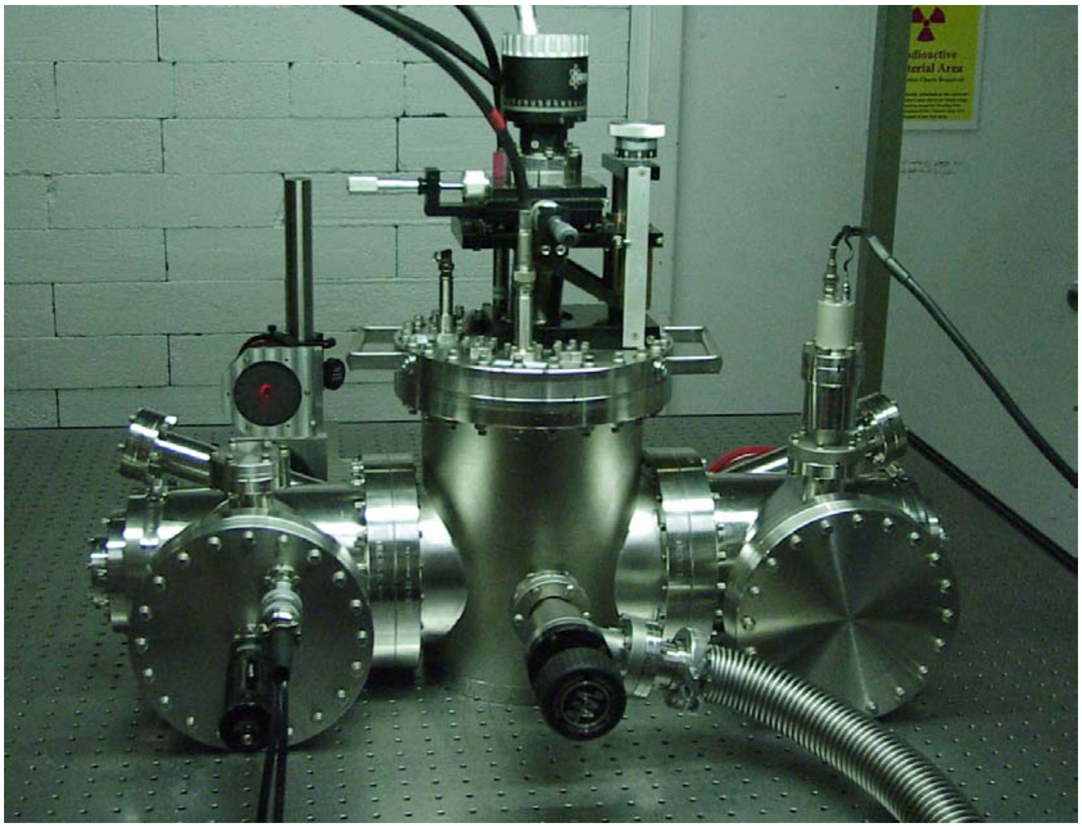
The plasma flow in the main capillary is turbulent. The time of the plasma propagation through the main capillary can be estimated as:

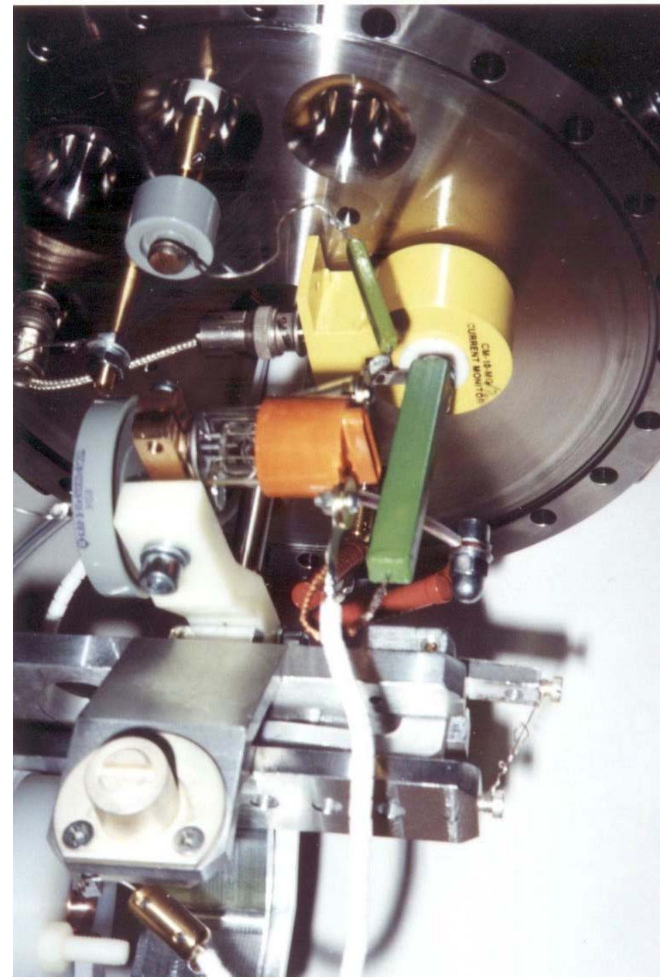
$$t = \frac{d}{k\xi c_s(0)} \exp\left(\frac{kL}{d}\right)$$

Where k and ξ are dimensionless turbulent heat conductivity and viscosity.
$k = 0.048$, $\xi = 0.25$,
$c_s = 4\times10^5$ cm/s.
For $d = 300$ µm, $L = 1.4$ cm
$t = 60$ µs.

[1]D. Kaganovich *et al.* Appl. Phys. Lett. **71,** 2925 (1997).

Plasma source

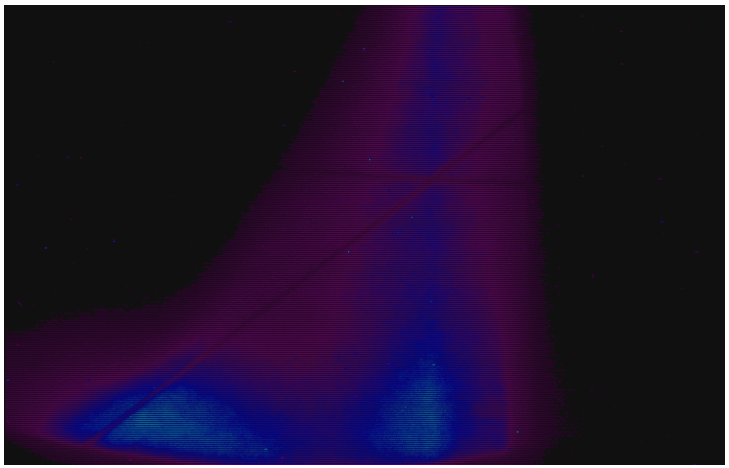


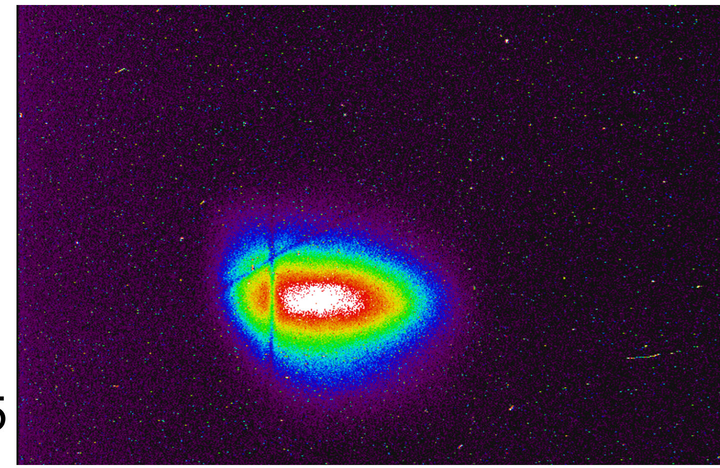


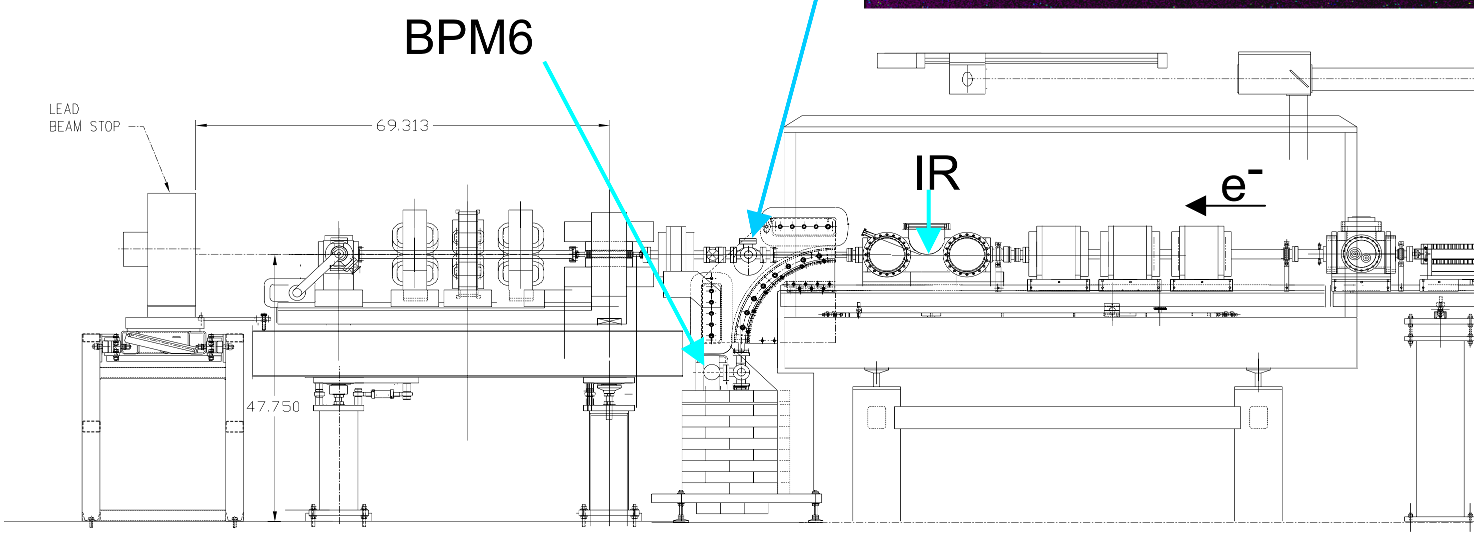
Electron beam observation points

BPM 6 image (90 degrees bend) X-beam energy, Y –horizontal profile of e-beam [~1.5% x 4 mm full screen]

BPM 5 image (straight ahead) X-horizontal, Y –vertical size of e-beam ~ 4mm x 4 mm full screen

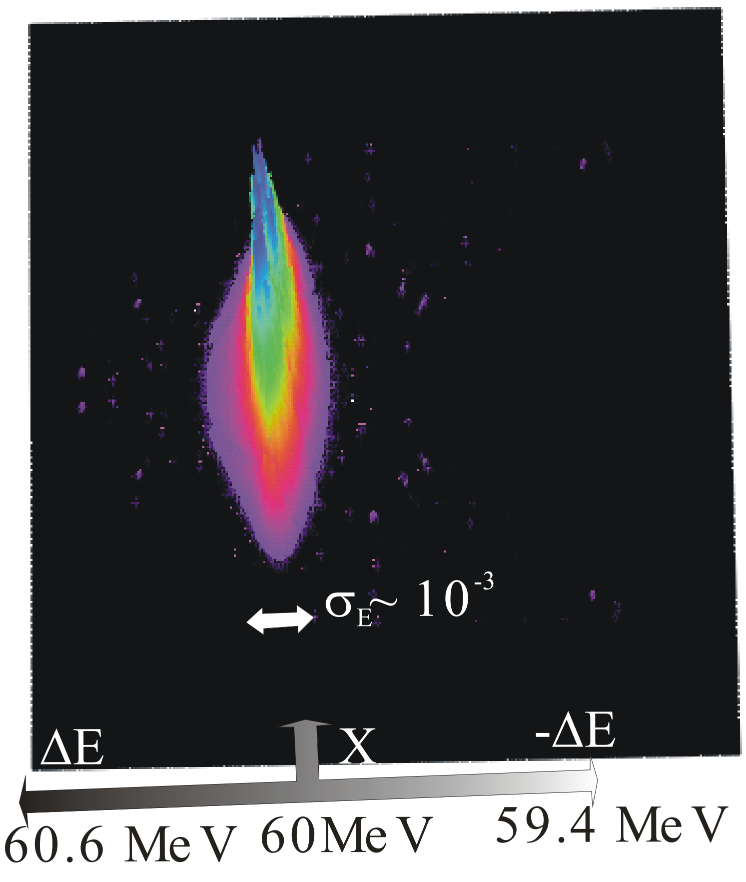




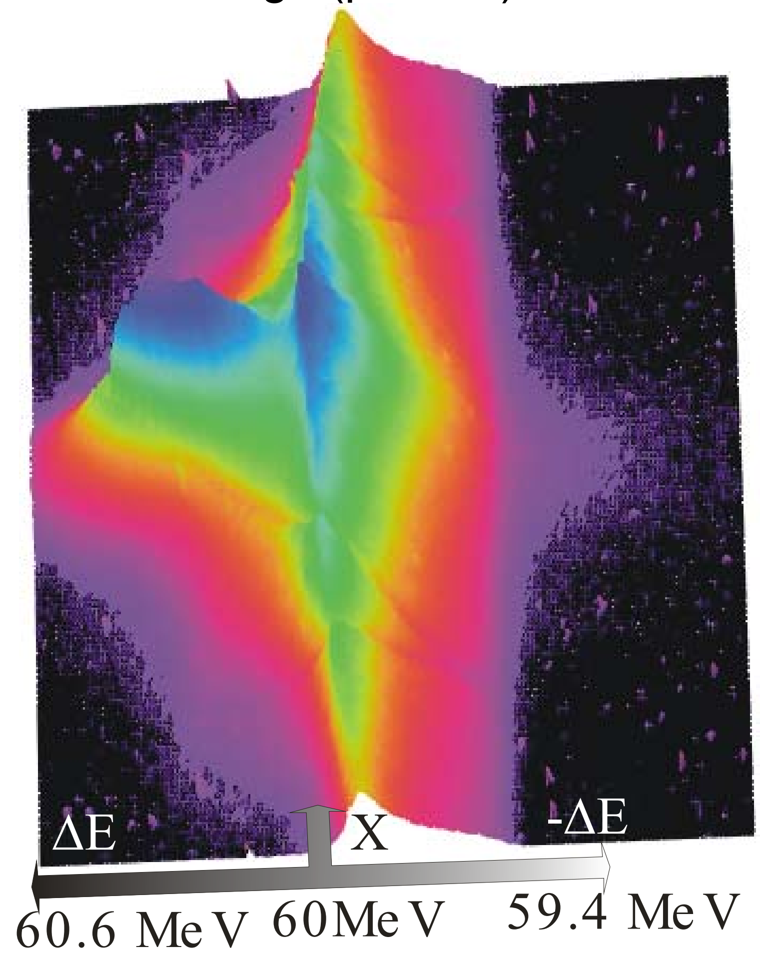


The picture

Discharge (plasma) off

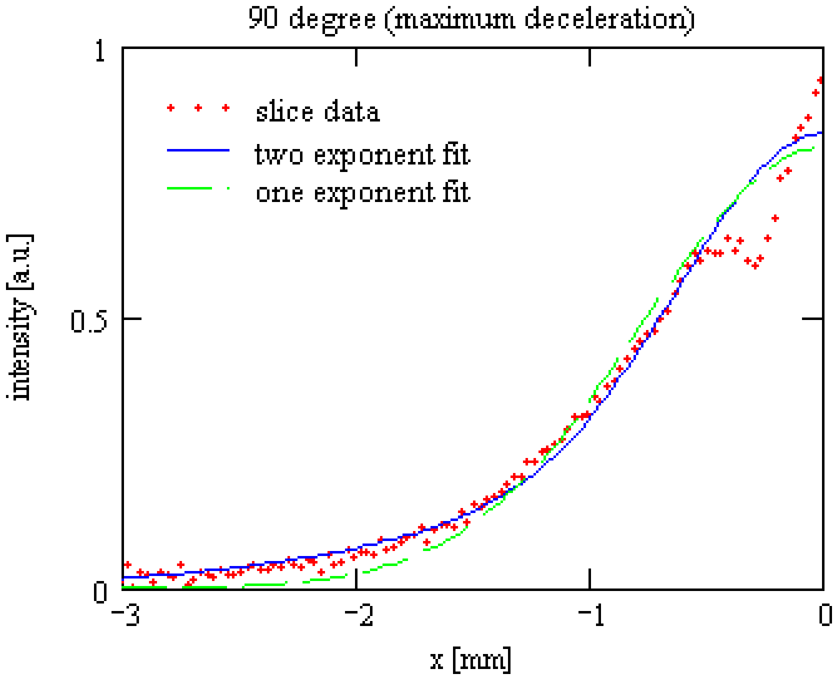


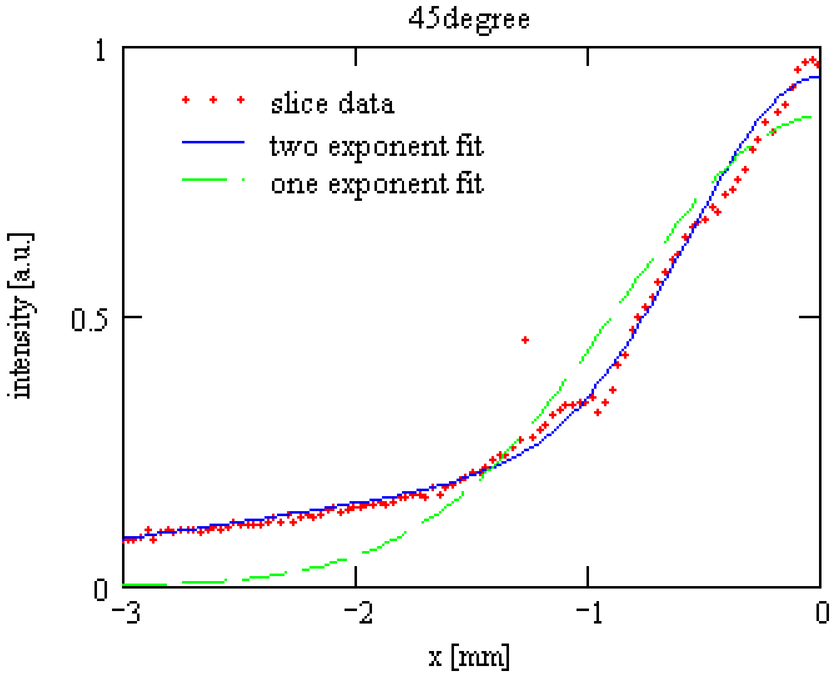
Discharge (plasma) on



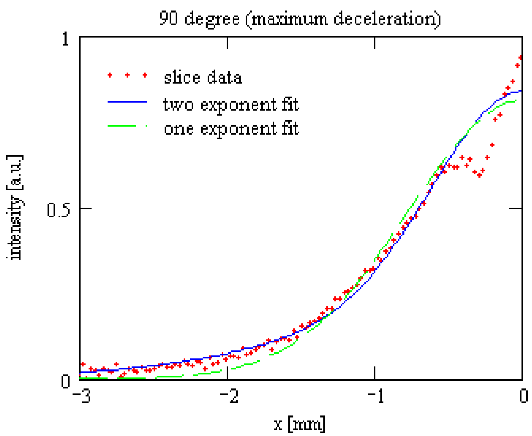
Energy distribution and transverse beam phase space dramatically changed after a 60 MeV, 0.5 nC, 3 ps (FWHM) e-beam passes through 17 mm of ~10^{17} plasma.

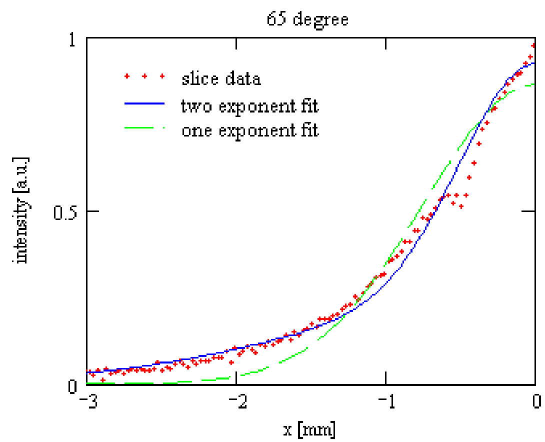
Focusing VS acceleration

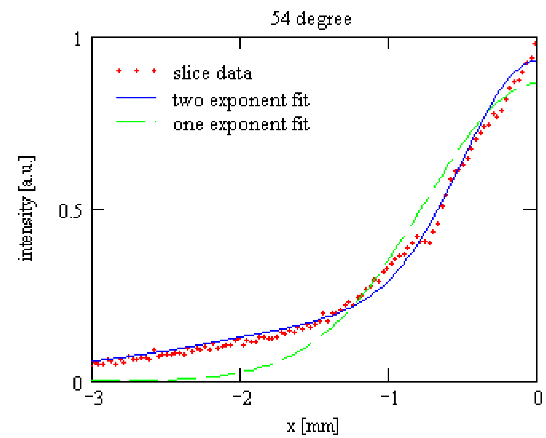


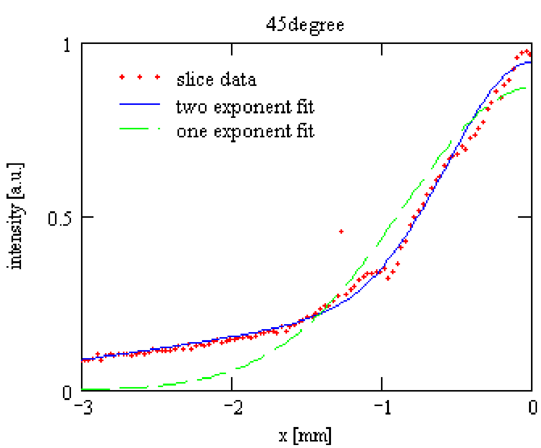


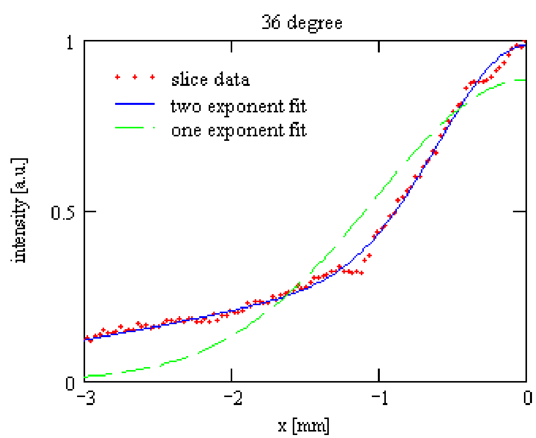
Focusing VS accelerating phase

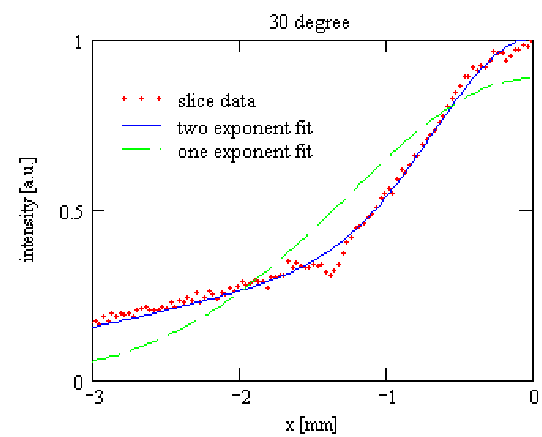




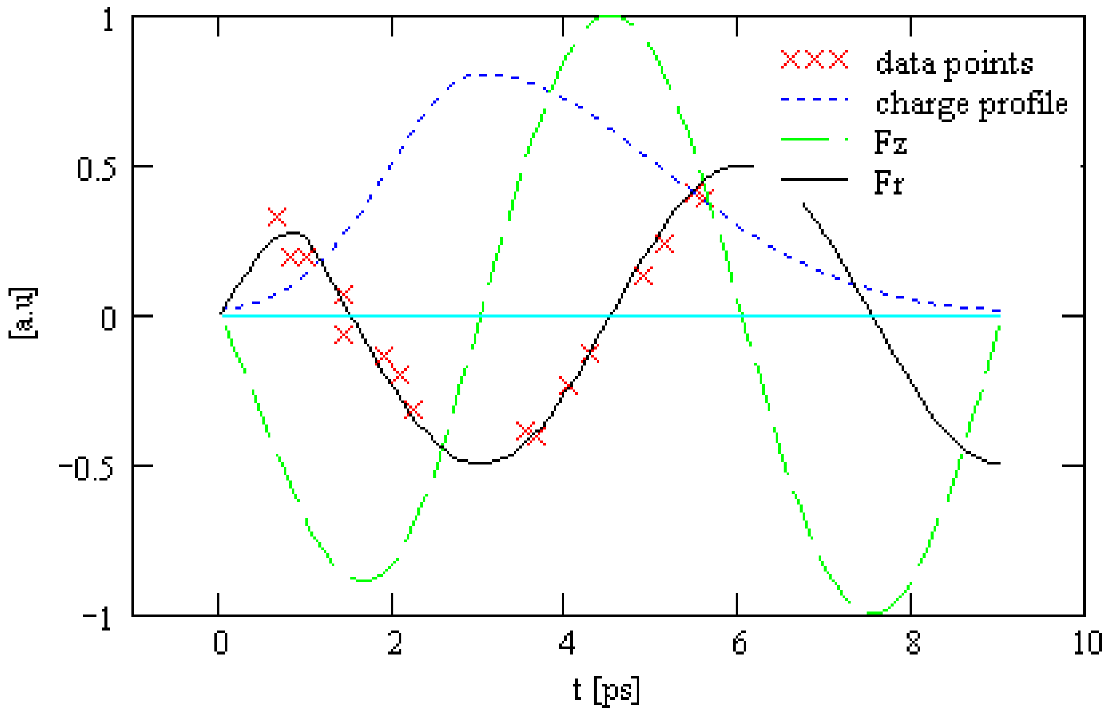








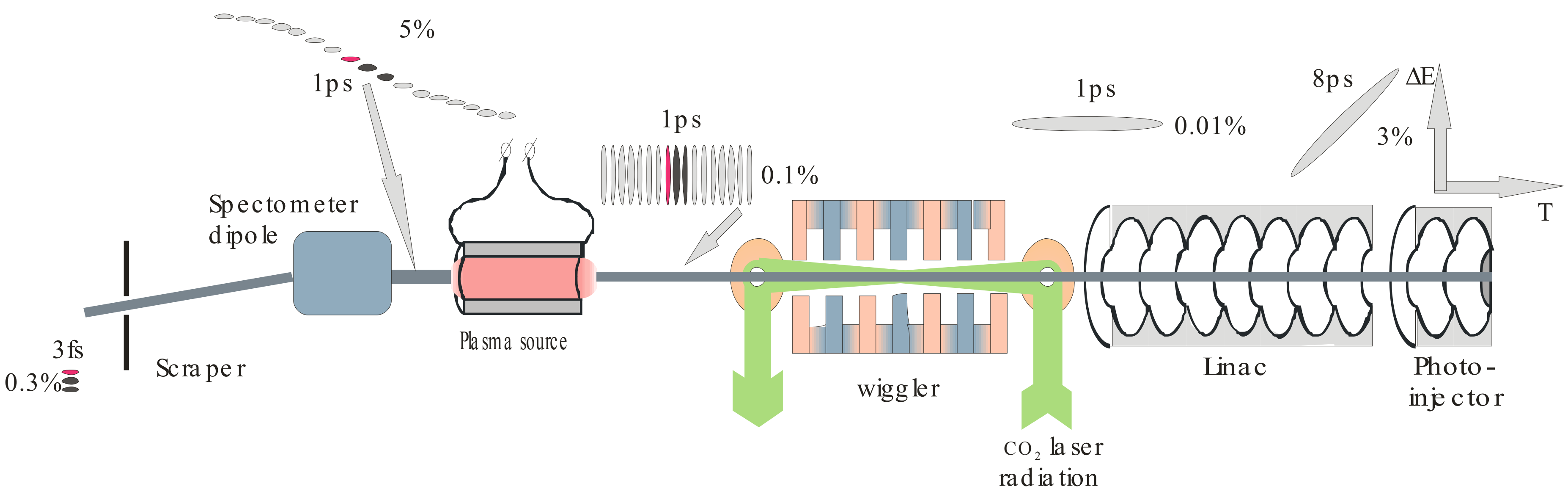
Correlation between longitudinal and transverse wakes phases



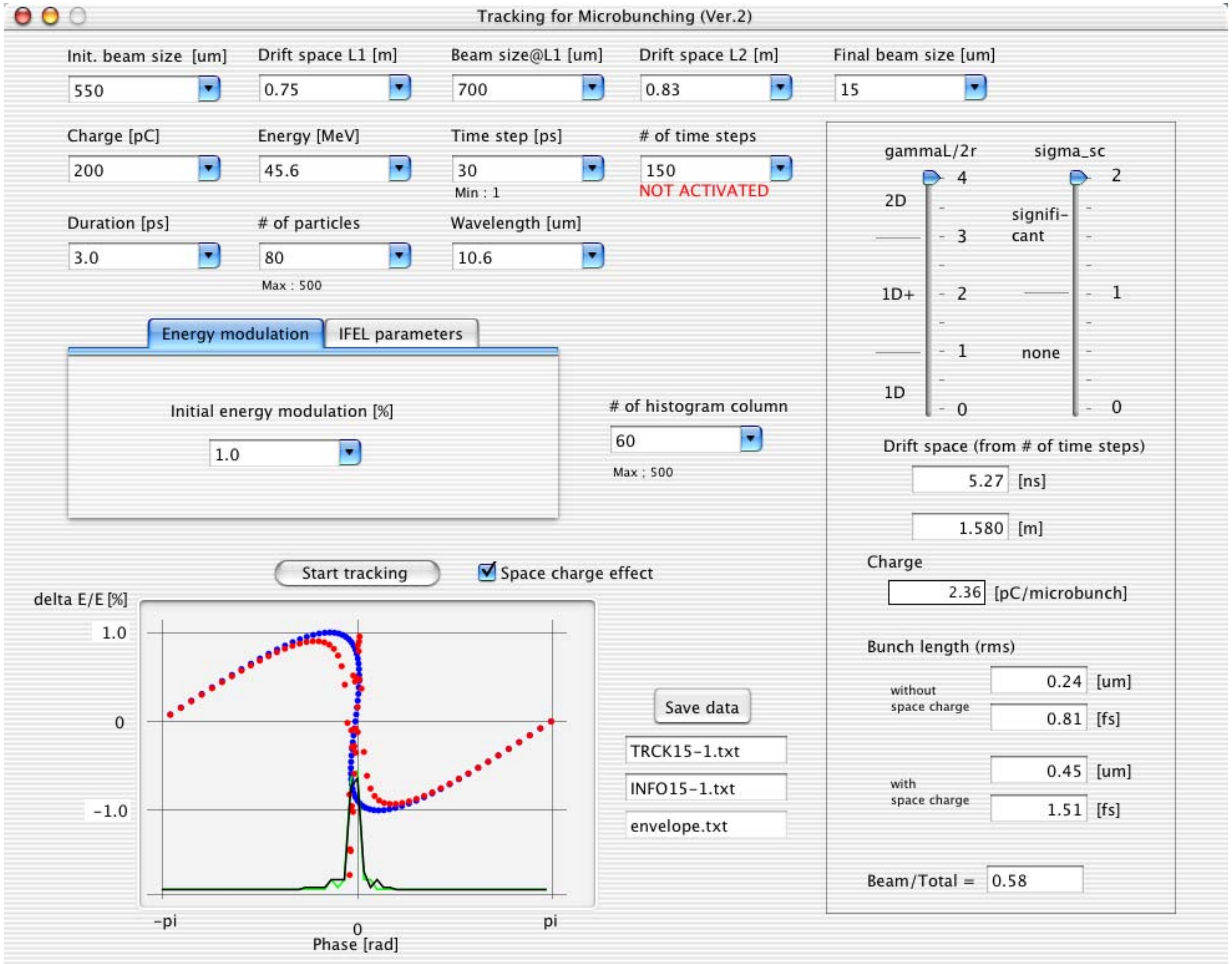
Beam size as a function of the wake phase. Solid lines schematically show expected longitudinal (blue) and transverse (magenta) wakes phases. Experimental points are reconstructed from the energy slices using double-Gaussian fit.

Short electron beam generation

Plasma source can be used to induce sufficient energy correlation along 1 ps train of e-beam micro bunches



Space charge issues in the microbunches



Plans

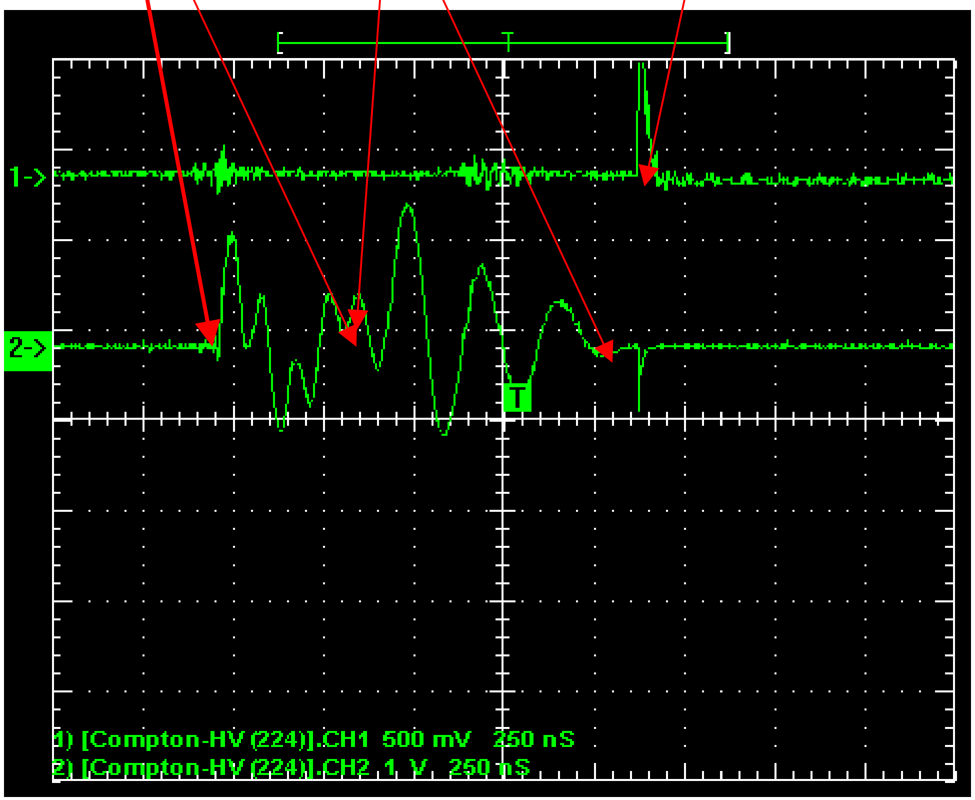
We are looking forward to collaboration with other groups on this subject

Discharge timing (delay set to 1.2 μs)

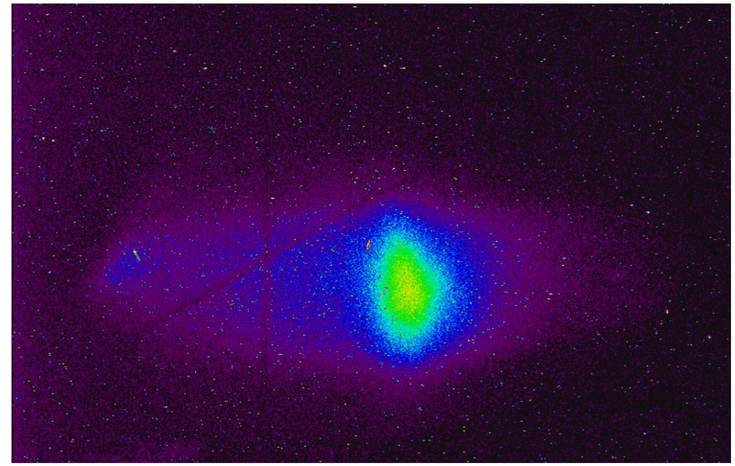
Triggering discharge

Main discharge

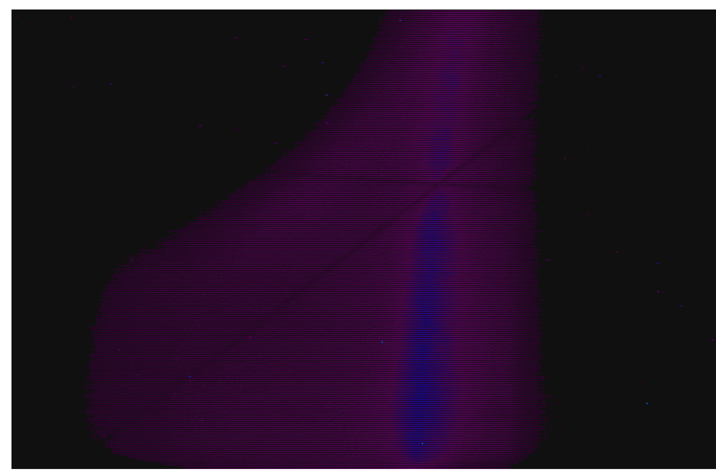
Electron beam



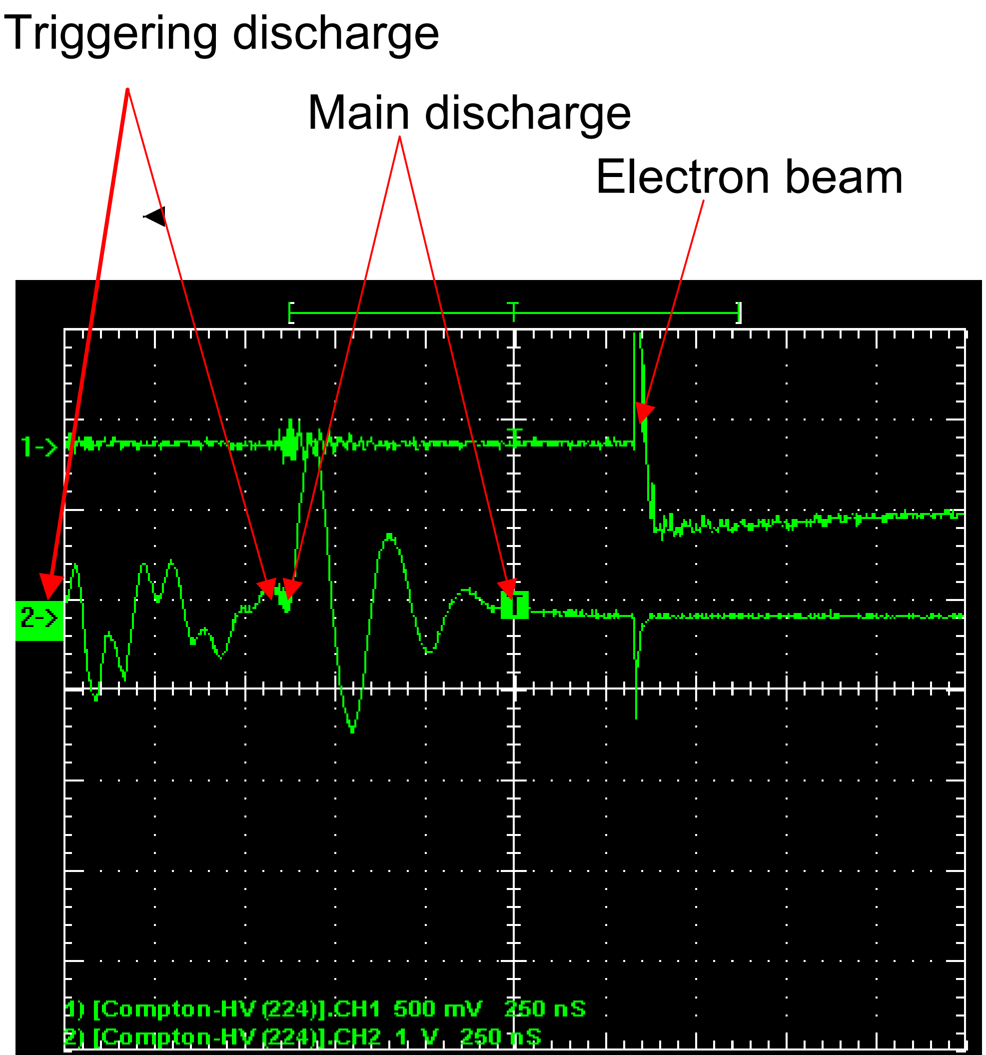
BPM5



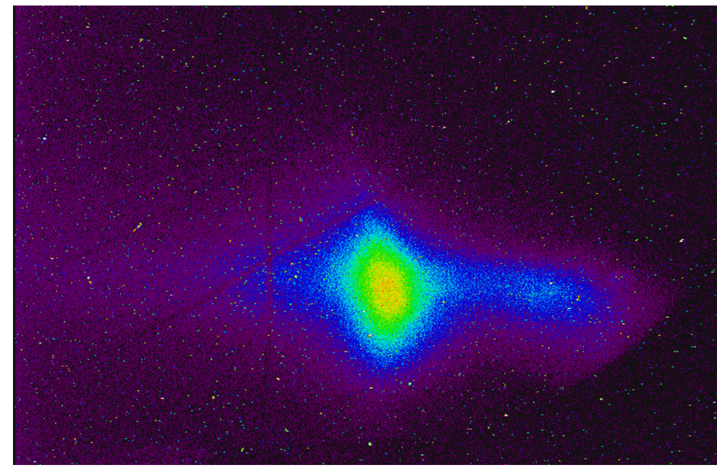
BPM6



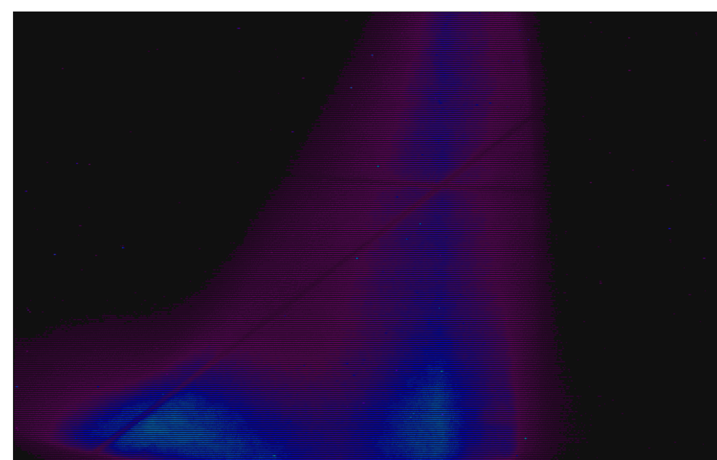
Discharge timing (delay set to 1.8 μs)



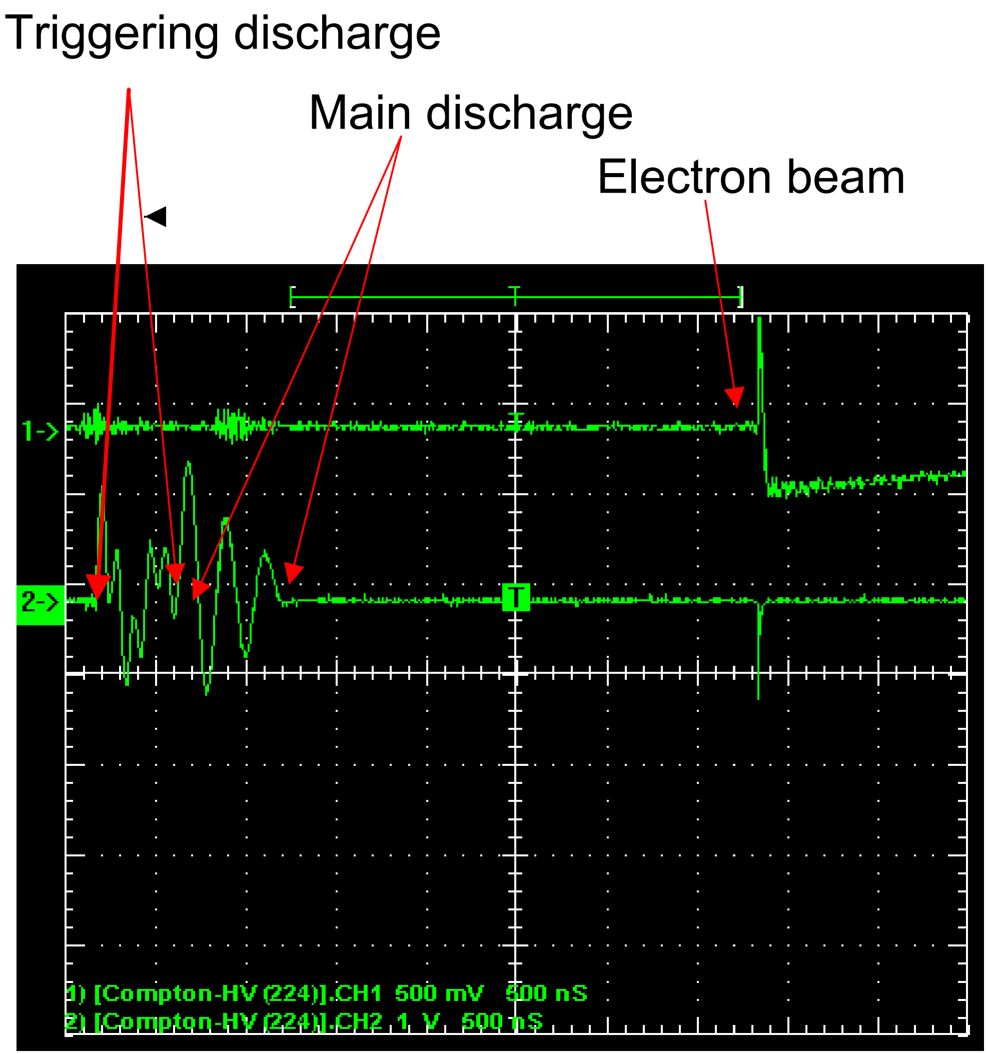
BPM5



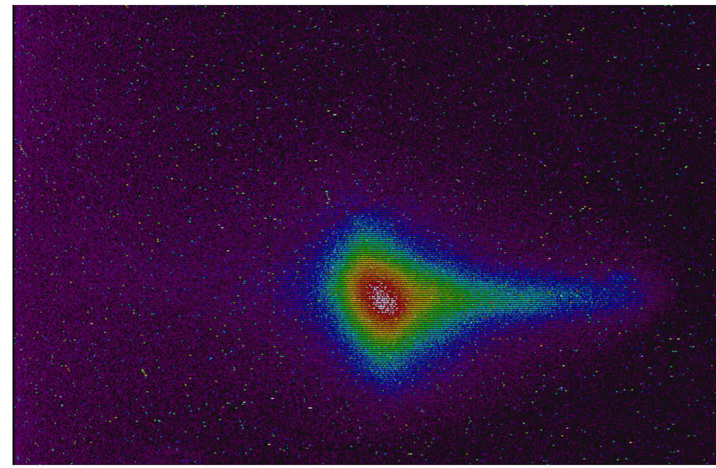
BPM6



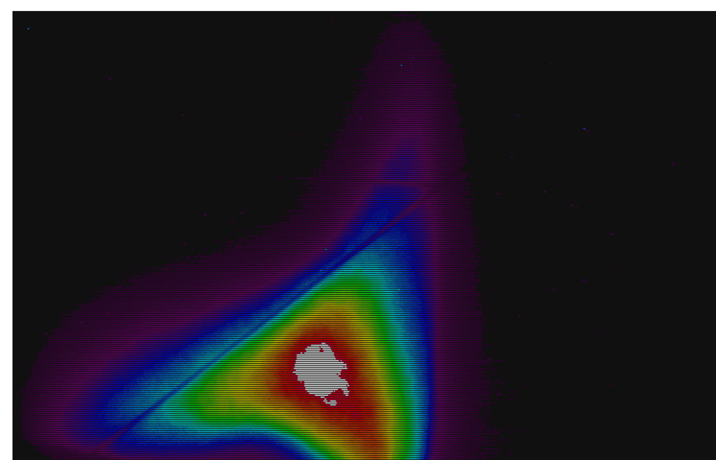
Discharge timing (delay set to 3.7 μs)



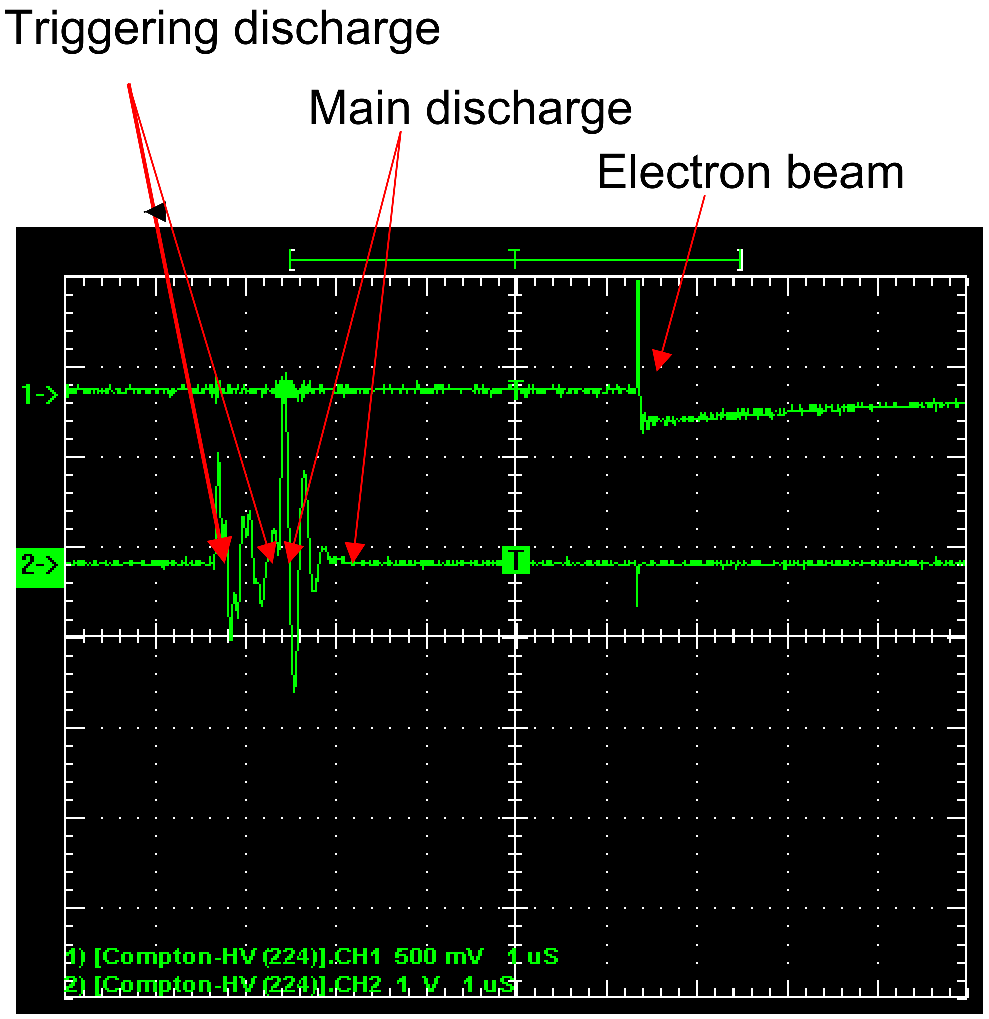
BPM5



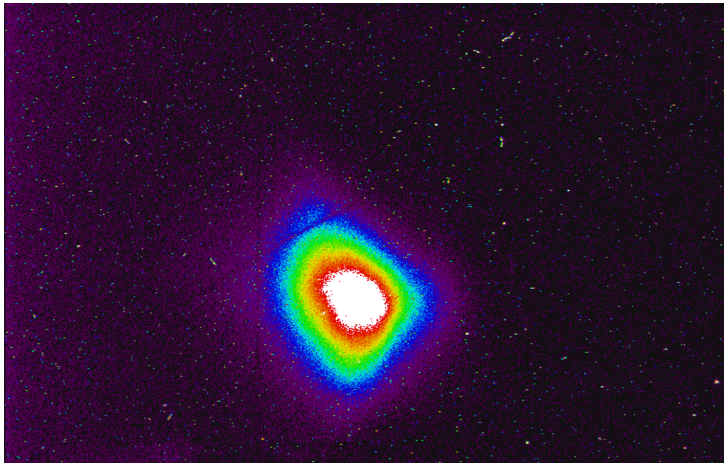
BPM6



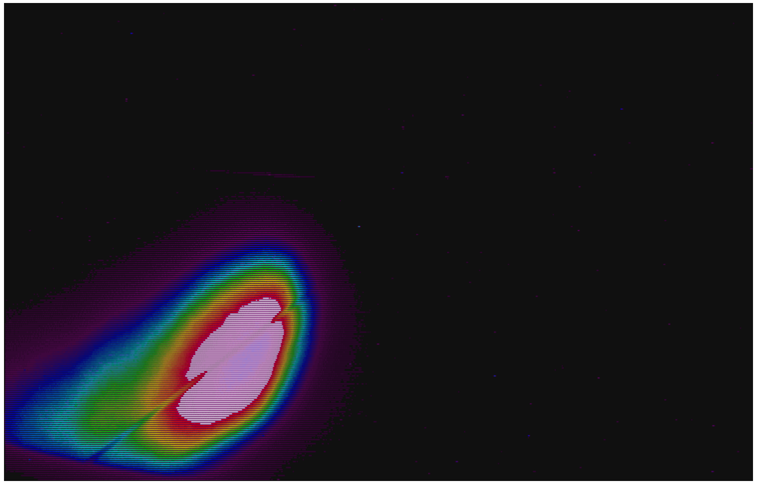
Discharge timing (delay set to 5 μs)



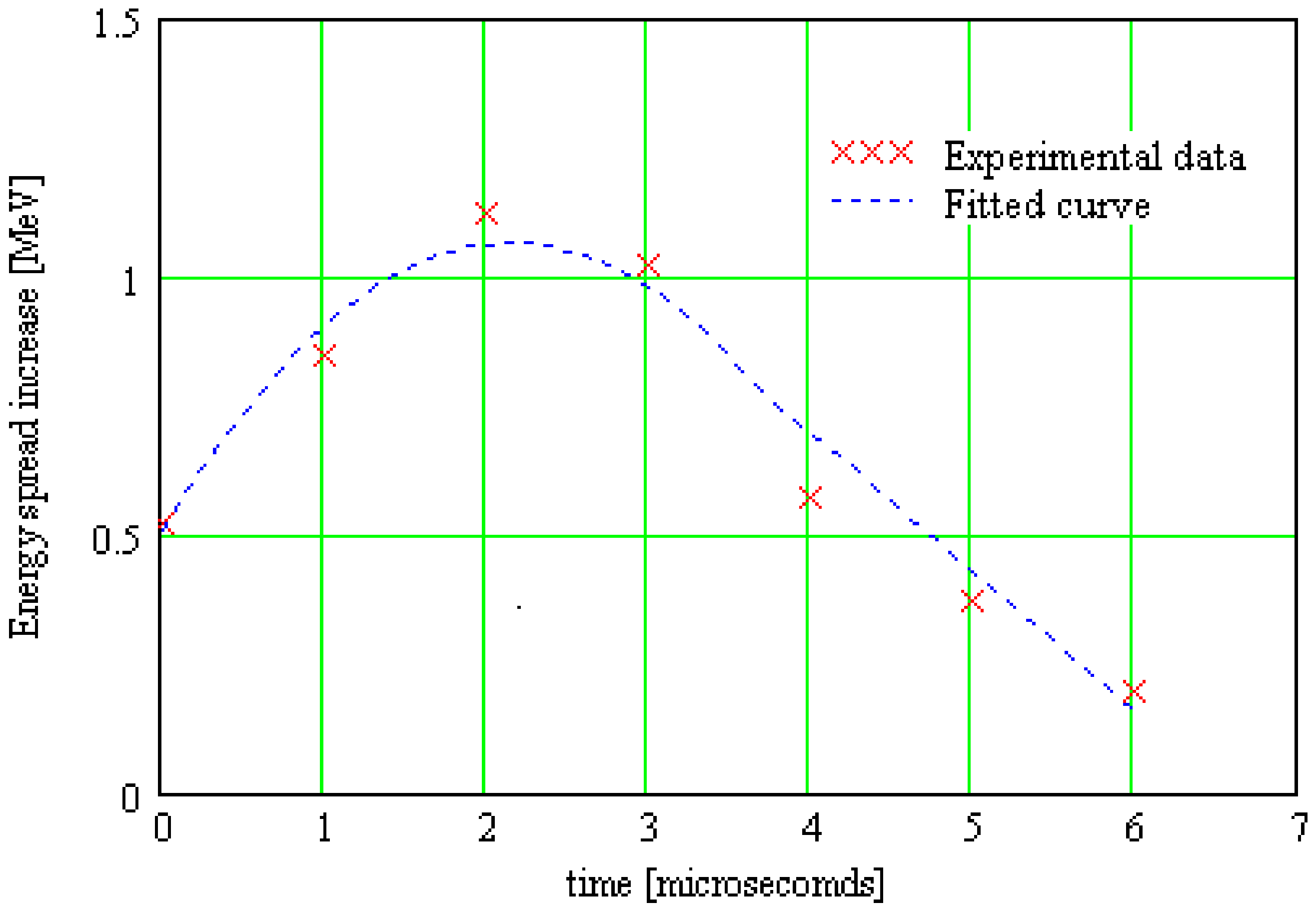
BPM5



BPM6



Acceleration VS time



Plasma density VS time